DIVISION OF TRAFFIC OPERATIONS
CALIFORNIA DEPARTMENT
OF TRANSPORTATION

Traffic Operations Manual

Ramp Metering Systems

Part 4 Ramp Metering Operations

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Section 1 Introduction

Ramp metering is a proven method of improving the efficiency of a freeway system by eliminating or reducing freeway congestion. There are a multitude of strategies to operate ramp meters. In a state as diverse as California, several factors influence these strategies. While these factors might appease the California Department of Transportation (Caltrans) and its partners at the local level, some of their long-term effects can be detrimental. Standardizing ramp metering operations provides several benefits. It improves equity and reliability for local jurisdictions to benefit from this method of congestion reduction. Consistent operational methods also provide a basis for tracking the cost of ramp metering operations. This will make it easier for transportation professionals—especially ramp metering practitioners—to collaborate on congestion reduction advancements.

This chapter is Caltrans' first attempt to standardize ramp metering operations across California. It is a living document that is meant to be periodically updated by a core team of seasoned transportation professionals. Proposed revisions for the next update should be emailed to the chief of the Headquarters Office of Traffic Management.

Topic 1 Purpose of This Document

The purpose of this chapter is to best describe how Caltrans operates ramp meters. The information in this chapter will improve the following:

- Standardization of new and existing ramp metering operations.
- Knowledge transfer for ramp metering practitioners.
- Constant ("24/7") ramp metering, whether or not the signal indications are illuminated.

The ramp metering operational criteria in this manual provide a guide for the engineer to exercise sound judgement in applying practices, consistent with traffic engineering principles, in the operation of ramp meters. This guidance allows for flexibility in applying operational principles and documenting operational decisions that take the context of the ramp meter location into consideration, which enables the engineer to tailor the operation of ramp meters, as appropriate, for the specific circumstances while maintaining safety.

Topic 2 Why Is Ramp Metering Effective?

According to the Federal Highway Administration (FHWA) Publication FHWA-HOP-14-20:

> Ramp meters are traffic signals installed on freeway on-ramps to control the frequency at which vehicles enter the flow of traffic on the freeway. Ramp metering reduces overall freeway congestion by managing the

> amount of traffic entering the freeway and by breaking up platoons that make it difficult to merge onto the freeway.

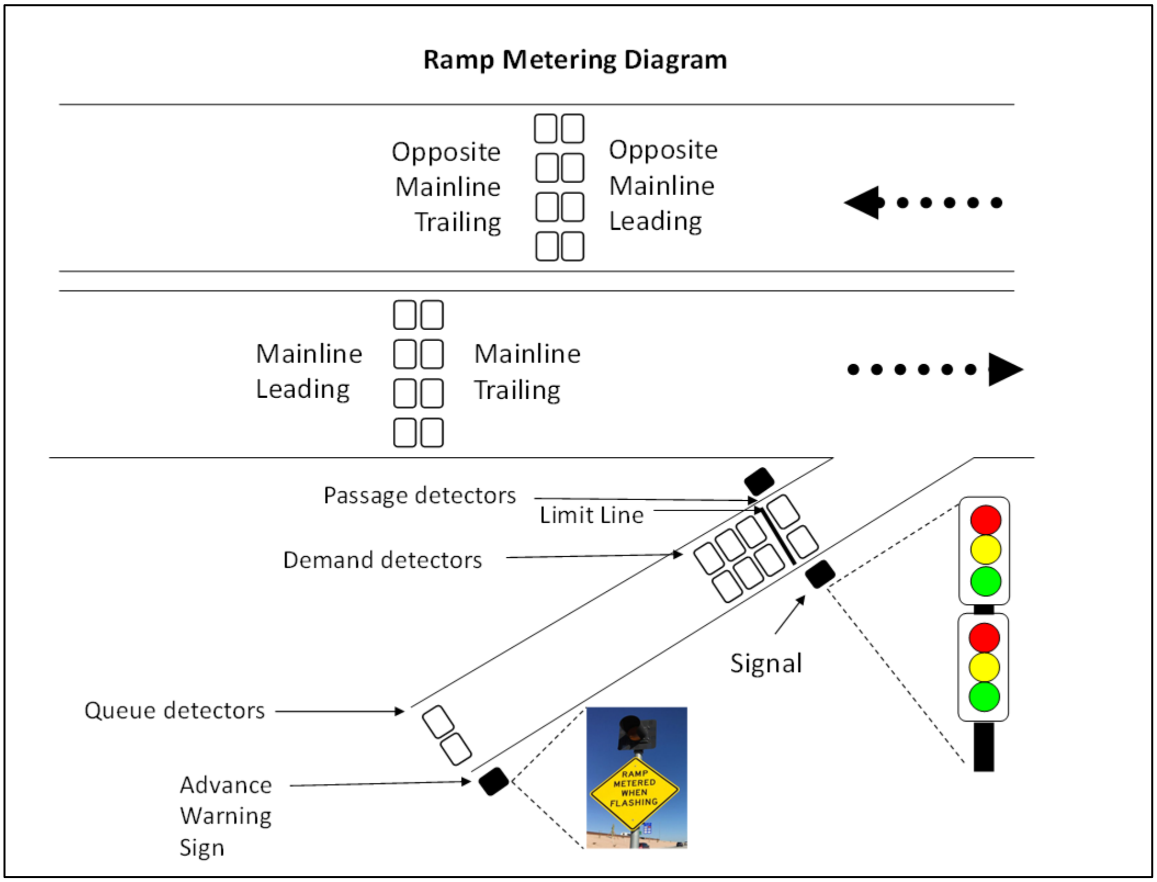
Publication FHWA-HOP-14-20 further states,

> Without ramp meters in operation, multiple vehicles merge in tightly packed platoons causing drivers on the mainline to slow down or even stop in order to allow vehicles to enter. The cascading slower speeds, both on the mainline and on the ramp, quickly lead to congestion and sometimes stop-and-go conditions. Ramp meters can break up the platoons by controlling the rate at which vehicles enter the mainline from the ramp…This allows vehicles to merge smoothly onto the mainline and reduces the need for vehicles on the mainline to reduce speed. In addition to breaking up platoons, ramp meters help manage entrance demand at a level that is near the capacity of the freeway, which prevents traffic flow breakdowns. Ramp meters are shown to reduce peak-hour lane occupancies (freeway density) and quicken recovery from mainline breakdown back to or below the critical occupancy threshold. Typical results include reductions in travel time, reductions in crash rates, and increased traffic speed.

Section 2 Overview

Topic 1 Basic Ramp Meter Layout

Figure 215-1 Typical Ramp Meter Layout



Topic 2 Essential Ramp Metering Components

A ramp metering location needs to have the following four essential components:

1. **Signal Heads**: Three-section indicators with red, yellow, and green indicators to inform drivers of what action to perform, such as stop, prepare to stop, and proceed.

   Note: In some locations, a lower signal head with two-section red and green indicators is installed. When a two-section indicator is installed, the lower signal head is referred to as "lower green" and shall be illuminated whenever either the green or yellow signal is illuminated on the upper signal head.

2. **Detectors:** The following detection is important (essential for traffic-responsive) for ramp metering operations:

- *Metered lane demand* for monitoring the presence of vehicles at the limit line.
- *Metered lane passage* for minimizing the length of metering green interval.
- *Metered lane queue* for detecting when a queue will extend onto a local roadway or, for a connector meter, onto the upstream freeway.
- *Mainline lane* for detecting volume, occupancy, and speed of vehicles in the freeway segment adjacent to the on-ramp. These data are used to determine the proper release rate during traffic-responsive ramp metering operations.

3. **Controller:** A Model 2070 controller is used to control the sequence and duration of ramp meter indications.
4. **Signage**: Proper signage provides clear communications to motorists with compliance information, such as:
   - Number of vehicles allowed to proceed onto the mainline with each metering green interval.
   - Advance warning signs to indicate that a ramp meter is currently in operation. When used, W3-8 signs are complemented with the addition of an advance warning beacon.
   - Special use lanes, such as high-occupancy vehicle (HOV) or bus lanes.

   Note: The 2014 *California Manual on Uniform Traffic Control Devices* provides the following guidance on advance warning signs in section 4I.03 of the document:

   When the ramp control signals are in operation, a RAMP METERED WHEN FLASHING (W3-8) sign (see Section 2C.37) or an overhead Activated Blank-Out “METER ON”(W88-2(CA), W88-3(CA)) message sign, or an Activated Blank-Out “PREPARE TO STOP” (W89(CA)) message sign should be installed in advance of the ramp control signal near the entrance to the ramp, or on the arterial on the approach to the ramp, to alert road users to the presence and operation of ramp meters. (See Figure 2C-6(CA)).

Topic 3 Ramp Metering Data Collection Components

The following components are essential for data collection used in typical traffic operations and management:

- **Communications**: The ramp metering systems must be in constant communication so that every 30 seconds it can transmit its traffic data and operational status to the Transportation Management Center (TMC) or other operating district’s central system.

- **Supplemental Detection**: Detectors, other than those described in Section 2, Topic 2 "Essential Ramp Metering Components," are desirable for collecting freeway data. They are located at the following:
    - **Opposite Mainline**: Lanes of freeway traffic that flow in the opposite direction to the mainline lanes into which the on-ramp traffic merges. Opposite mainline detection monitors each lane's vehicle speed, flow, and occupancy.
    - **Collector–Distributor (C-D)**: C-D detection monitors each lane's vehicle flow and occupancy.
    - **Off-Ramp**: Off-ramp detection monitors each lane's vehicle flow and occupancy.
    - **Metered On-Ramp**: Some metered on-ramps have count detectors. Count detectors are located downstream of the limit line and upstream of the merge point. A count detector monitors each lane's vehicle speed, flow, and occupancy.
    - **Non-Metered On-Ramp**: Non-metered on-ramp detection monitors each lane's vehicle flow and occupancy.

Topic 4 Ramp Metering Remote Operation

For remote operation, the ramp metering systems must be in constant communication with the operating district's central system.

Section 3 Operational Requirements

Topic 1 General

The primary objective in operating ramp meters is to meter traffic onto freeways to maximize throughput of the freeway mainline lanes. A ramp meter manages the rate at which vehicles flow from the on-ramp onto the mainline and breaks up vehicle platoons into the smallest size possible to minimize the effects of merging on-ramp traffic on mainline traffic flow.

Topic 2 Hours of Operation

To allow ramp metering during both recurring and non-recurring congestion, each ramp meter should:

- Be operated 24 hours a day, seven days a week, at locations where local or central traffic-responsive metering is available and adequate maintenance and operations personnel are available to handle operational issues.

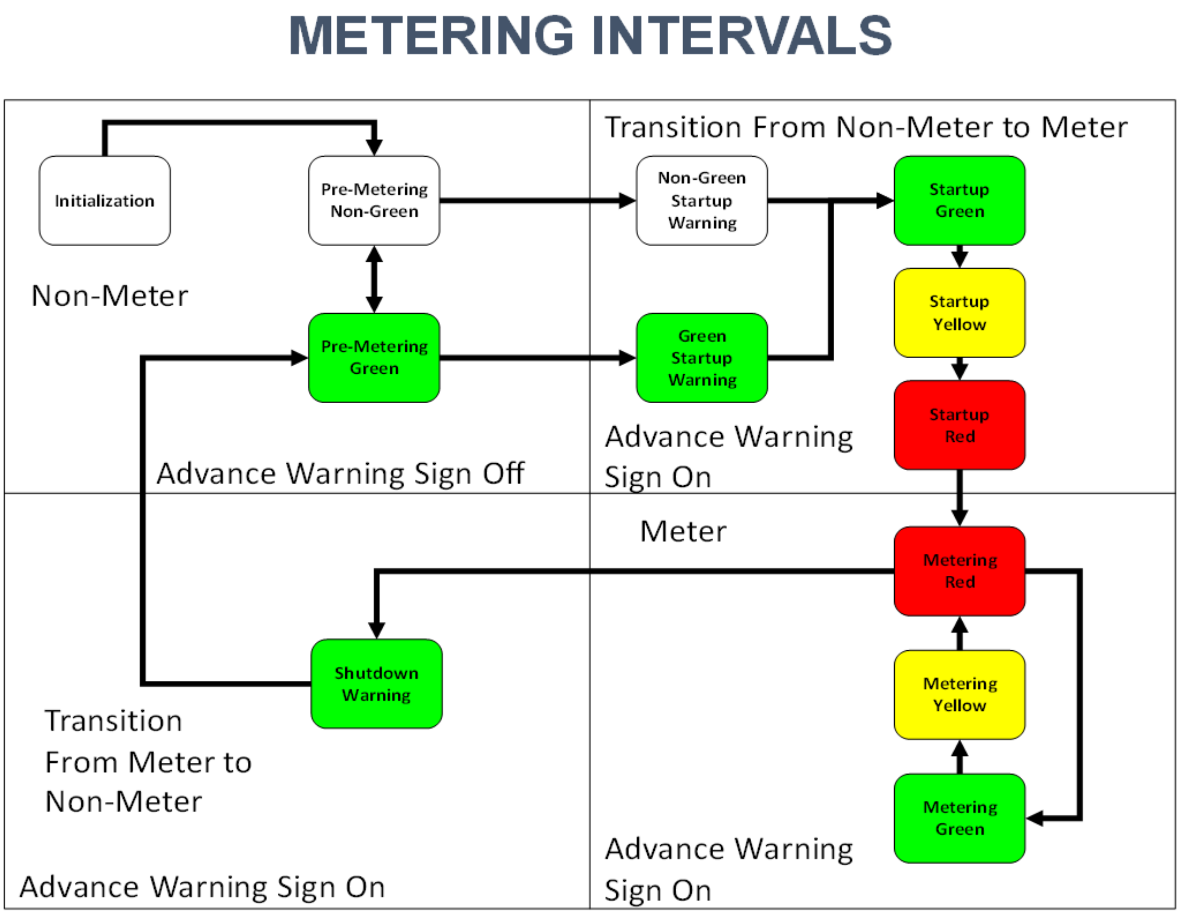
  or

- If the ramp meter is not operated 24 hours a day, seven days a week, then the ramp meter should be operated for the maximum number of hours as necessary to minimize congestion. It should begin operating before congestion materializes and end after it has dissipated.

Topic 3 Ramp Metering Phase Intervals

Typical ramp metering intervals are shown in Figure 215-2. Special metering circumstances are not shown. For a more comprehensive graphic representation and description of metering intervals, see the following content in the *National Transportation Communications for Intelligent Transportation Systems Protocol* 1207 v02: Figure 3, “Metered Lane Interval State Diagram,” Section 1.6, “Supplemental Figures,” and Annex A, “Ramp Meter Control Unit Operations Description.”

Figure 215-2 Metering Intervals



Ramp meters shall have the following ramp metering phase intervals (see Figure 215-2):

1. **Initialization**: This phase interval occurs only during ramp metering implementation or after a power disruption to the controller and occurs before advancing to the pre-metering non-green interval. The controller is "booting up." Advance warning signs shall be off.
2. **Pre-Metering Non-Green**: Ramp meters are not actively metering and traffic is relatively light. The signal indications are off. Advance warning signs shall be off.
3. **Pre-Metering Green**: Ramp meters are not actively metering and traffic is relatively light. Green indications are on. Advance warning signs shall be off.
4. **Non-Green Startup Warning**: This interval is intended to warn motorists that ramp meters are about to cycle. The green indications during this transition from the non-metering state to the metering state are off. Advance warning signs shall be on.
5. **Green Startup Warning**: This interval is intended to warn motorists that ramp meters are about to become operational. The green indications during this

transition from the non-metering state to the metering state are on. Advance warning signs shall be on.

6. **Startup Green**: The green indications shall be on during this interval, which is part of the transition from the non-metering state to the metering state. Advance warning signs shall be on. The duration of this interval should be between 15.0 seconds and 120 seconds.
7. **Startup Yellow**: The yellow indications shall be on during this interval and are part of the transition from the non-metering state to the metering state. As the initial yellow phase of a period of ramp metering, it needs to be similar to a traffic signal's yellow indications (see Section 13, "Startup and Metering Yellow Time Calculation"). Advance warning signs shall be on. The duration of this interval should be between 1.5 seconds and 10.0 seconds.
8. **Startup Red**: The red indications shall be on and are part of the transition from the non-metering state to the metering state. Advance warning signs shall be on. The duration of this interval should be between 1.0 second and 10.0 seconds.
9. **Metering Red**: The interval during the typical metering cycle requiring motorists to stop. The red indications shall be on. Advance warning signs shall be on. The duration of the minimum red time shall be between 1.0 second and 2.5 seconds.

   The metering red time interval shall be calculated using the following formula:

   $$Metering\ Red\ Time = Cycle\ Time - (Last\ Metering\ Green\ Time + Last\ Metering\ Yellow\ Time)$$

10. **Metering Yellow**: The interval during the metering cycle requiring motorists to prepare to stop. The yellow indications shall be on. This interval is not used during one-car-per-green traffic-responsive ramp metering. Advance warning signs shall be on. The metering yellow interval shall be terminated when the elapsed interval time exceeds the configured metering yellow time. See Section 13, "Startup and Metering Yellow Time Calculation" for calculated startup yellow time values.
11. **Metering Green**: The interval during the typical metering cycle that allows motorists to cross the limit line. The green indications shall be on. Advance warning signs shall be on. A minimum green time of 1.0 second shall be used. When the passage detector is operational, the metering green interval shall terminate:

    - When the elapsed interval time exceeds the maximum green time;

      or

    - For one or two vehicles per green, the passage detector is actuated and the elapsed interval time exceeds the minimum green time;

      or

    - For three vehicles per green, the passage detector is actuated twice and the elapsed interval time exceeds the minimum green time.

Note: Three vehicles per green is used in District 7 at some locations, however the practice is not encouraged.

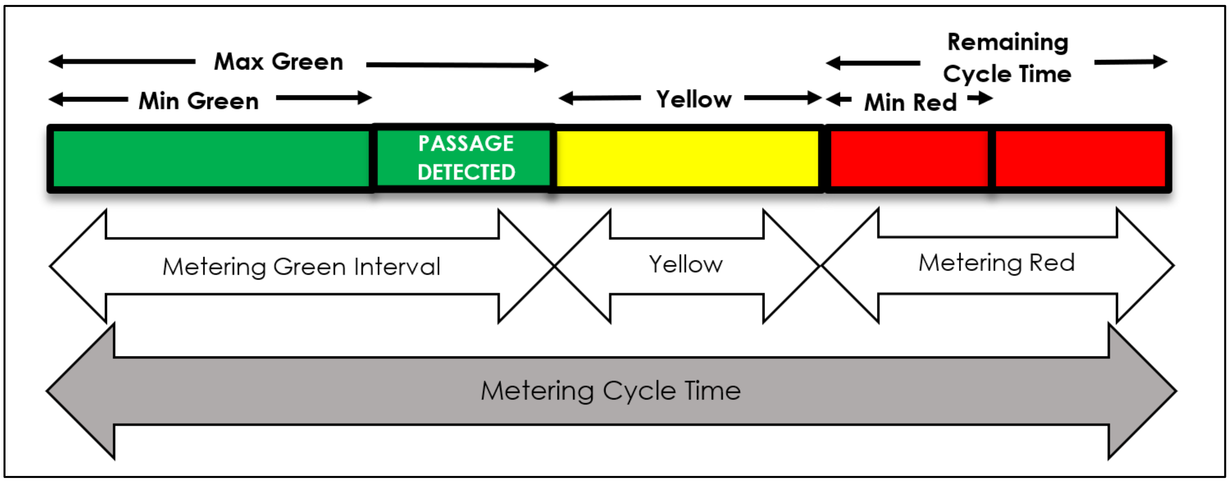
When the passage detector is not operational, the metering green interval shall terminate when the elapsed interval time exceeds the maximum green time.

12. **Shutdown Warning**: This interval is used to warn motorists when the metered lane signal is in transition from the metering state to the non-metering state since vehicles may still be queued at the limit line. The green indication shall be on. Advance warning signs shall be on.

Topic 4 Metering Cycle Time

Figure 215-3 shows metering cycle time.

Figure 215-3 Metering Cycle Time



Note: Remaining cycle time is the additional red cycle time needed to meet cycle length.

Topic 5 Metering Modes (Requested Actions)

Ramp meters shall have the following ramp metering modes:

- **Fixed-Rate**: Ramp meter shall actively meter and have fixed green, yellow, and red interval lengths.
- **Traffic-Responsive**: Ramp meter shall actively meter at a determined metering plan rate based upon the measured mainline flow, occupancy, and speed, and compare those values to the corresponding thresholds in the selected metering plan. The mainline flow, occupancy, and speed may be measured adjacent to the on-ramp, or over the length of a freeway segment. Queue override may be selected as a highest priority.

- **Rest-In-Dark**: Metered lane shall advance to the pre-metering non-green interval.
- **Rest-in-Green**: Metering intervals shall advance to the pre-metering green interval.

Topic 6 Command Source Priority

The ramp meter shall at a minimum have the following command source priorities:

- **Manual**: Maintenance and operations personnel test controller operations in the field.
- **Communications**: TMC or other remote operation facility remotely selects any ramp meter mode and activates and deactivates ramp metering operations.
- **Time of Day**: Controller operates in any selected metering mode based on the current time of the day and day of the week.

Topic 7 Time-of-Day Plans

The ramp meter shall have the ability to set a minimum of 12 time-of-day plans.

Each time-of-day plan shall have:

- A start time using a 24-hour clock format.
- The day of the week each event is supposed to start. The recommended order is:
    1. Sunday
    2. Monday
    3. Tuesday
    4. Wednesday
    5. Thursday
    6. Friday
    7. Saturday
    8. Holiday
- The selected metering mode (such as fixed-rate, traffic-responsive, rest-in-dark, rest-in-green).
- For each entry that has a fixed-rate metering mode, a configured discharge rate in vehicles per hour (VPH).
- For each entry that has a traffic-responsive metering mode, a selected plan and a discharge rate to use if all mainline detection is no longer working.

Topic 8 Holiday Tables

The purpose of the holiday tables is to operate the controller in a non-standard time-of-day mode on specifically selected days, usually state holidays.

The user shall have the ability to configure at least 12 holidays per year.

Typical fixed and floating holidays are shown in Tables 215-1 and 215-2 below.

Table 215-1 Typical Fixed Holidays for the State of California

Holiday	Month	Day
New Year's Day	January	1
Cesar Chavez Day	March	31, or if on Sunday, April 1
Independence Day	July	4
Veteran's Day	November	11
Christmas Day	December	25

Table 215-2 Typical Floating Holidays for the State of California

Holiday	Month	Week	Day
Martin Luther King Day	January	3	Monday
Presidents' Day	February	3	Monday
Memorial Day	May	Final	Monday
Labor Day	September	1	Monday
Thanksgiving	November	4	Thursday
Day after Thanksgiving	November	4 or 5, as applicable	Friday

Topic 9 Metered Lane Signal Service Modes

The purpose of the metered lane signal service mode is to stagger the release of vehicles between two or more adjacent lanes that are in the same dependency group.

The following signal service mode algorithms shall be available:

- **Mutually exclusive (MUTEX)**: Only one lane within the dependency group can be in the metering green interval at any time.
- **Fractional offset**: The next allowable metering green interval start time for any metered lane is calculated as:

$$Next\ Green\ Interval\ Time = Cycle\ Time\ \div Number\ of\ Lanes\ in\ the\ Group$$

For example, if the discharge rate is 600 VPH, the resulting cycle rate is 6.0 seconds. If there are 3 metered lanes, then 6.0 seconds ÷ 3 lanes would be 2.0 seconds per lane. The next lane in sequence can advance to the metering green interval no sooner than 2.0 seconds after another metered lane within the dependency group has started its metering green interval.

Topic 10 Ramp Metering Transition Sequences

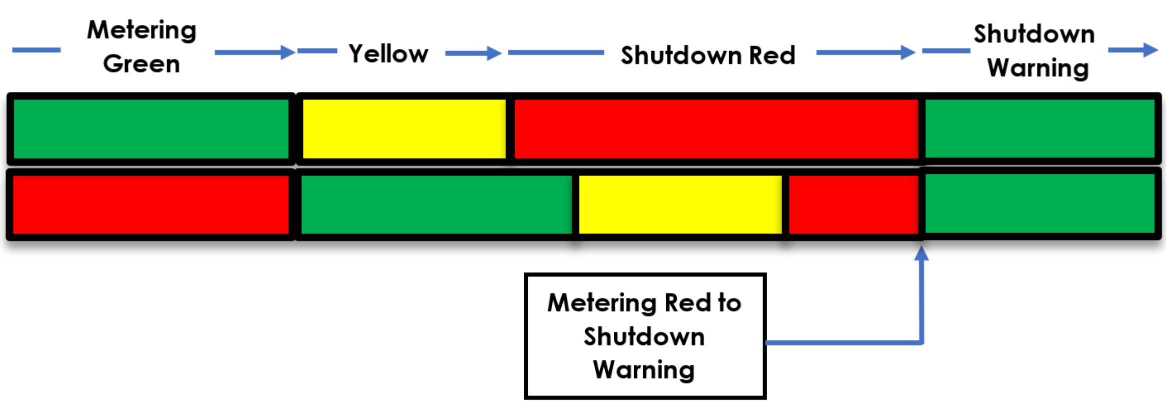
The ramp meter shall have the following five transition sequences:

1. From the initialization (boot-up) interval to the pre-metering non-green interval.
2. From the pre-metering non-green interval to the pre-metering green interval.
3. From the pre-metering green interval to active metering.
4. From active metering to the pre-metering green interval.
5. From the pre-metering green interval to the pre-metering non-green interval.

Metered lanes within the same dependency group shall transition in the same sequence concurrently.

Metered lanes within the same dependency group shall not begin their transition from active metering to the pre-metering green interval unless all meter heads are currently in the metering red interval. A visual representation of a two-lane metered ramp is shown in Figure 215-4.

Figure 215-4 Transition Sequence



Note: Before transitioning from metering to non-metering operations, all metered lanes shall be in the shutdown red interval.

Topic 11 Rest-In-Dark

If the mainline is not congested and if the pre-metering green time has elapsed, ramp meters shall advance to the pre-metering non-green (rest-in-dark) phase interval.

Topic 12 Advance Warning Sign

At ramp meter locations where advance warning signs are installed but no longer functional, consideration shall be given to disabling the ramp meter until the advance warning sign is repaired.

If a pedestrian-head type advance warning sign is installed at a location, it shall not flash.

Section 4 Traffic-Responsive Operation

Topic 1 General

Traffic-responsive ramp meters shall have discharge rates based upon the current volume, occupancy, and speed at the adjacent mainline lanes' detection stations.

Topic 2 Maximum Pre-Metering Green Parameter

The purpose of the maximum pre-metering green parameter is to limit the maximum number of minutes the ramp meter will remain in the pre-metering green interval before advancing to the next. It is recommended that there is a maximum pre-metering green parameter with the settable range of 0 to 255 minutes, in 1-minute increments. The ramp meter shall remain in the pre-metering green interval while the mainline traffic's volume, occupancy, and speed are continuously less than the traffic-responsive volume, occupancy, and speed thresholds required for active metering. More specifically:

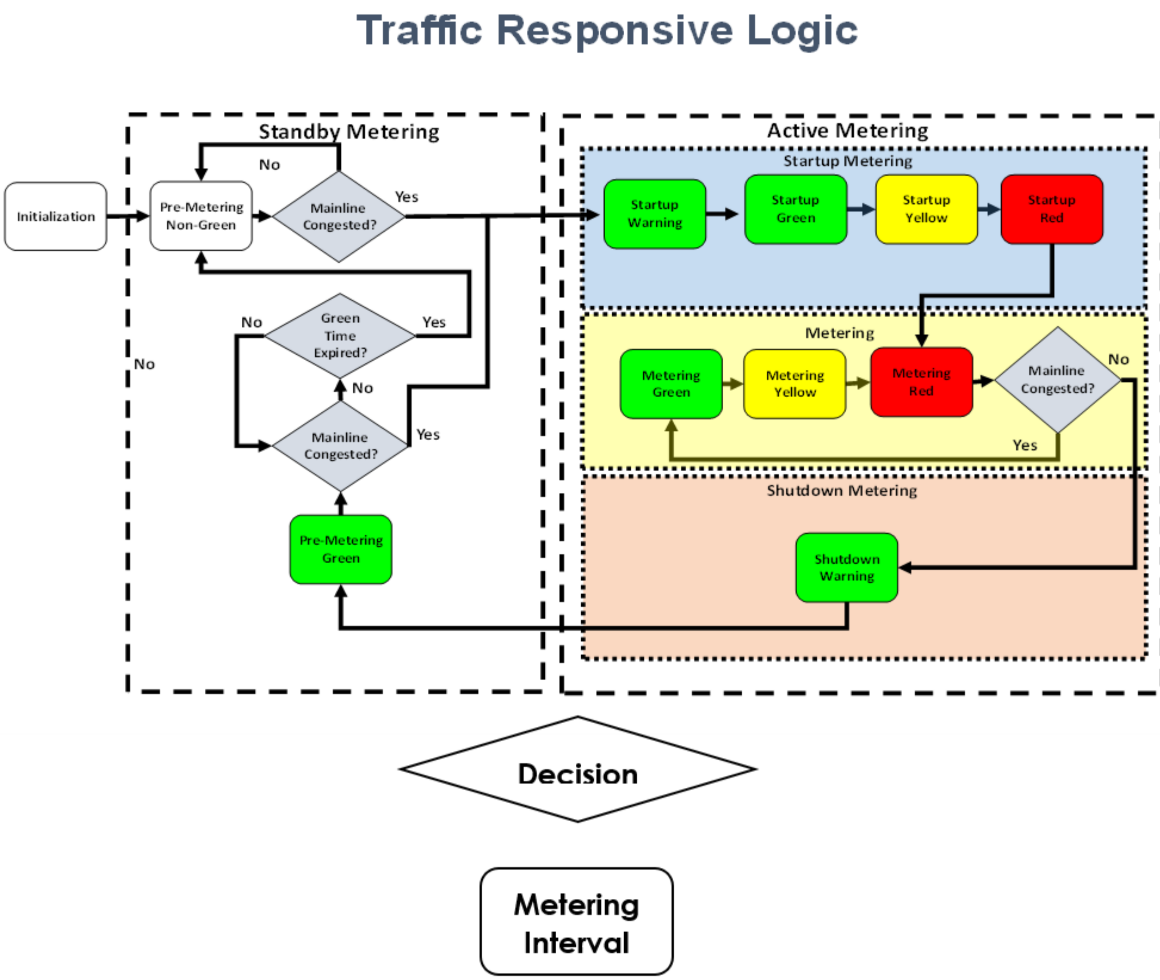
- A maximum pre-metering green parameter value of 0 minutes shall cause the controller to advance from the pre-metering green to the pre-metering non-green interval immediately when the mainline traffic is below the threshold required for active metering. This is for when the ramp meter will not rest in green during non-peak hours.
- A maximum pre-metering green parameter value of between 1 and 254 minutes shall cause the controller to advance from the pre-metering green to the pre-metering non-green interval when the mainline traffic is below the threshold required for active metering for more than the configured number of minutes.

A maximum pre-metering green parameter value of 255 minutes shall cause the controller to remain in the pre-metering green interval indefinitely while the mainline traffic is below the threshold required for active metering.

The recommended setting for the maximum pre-green parameter is 20 minutes.

Traffic-responsive operations shall follow the logic shown in Figure 215-5.

Figure 215-5 Traffic-Responsive Logic



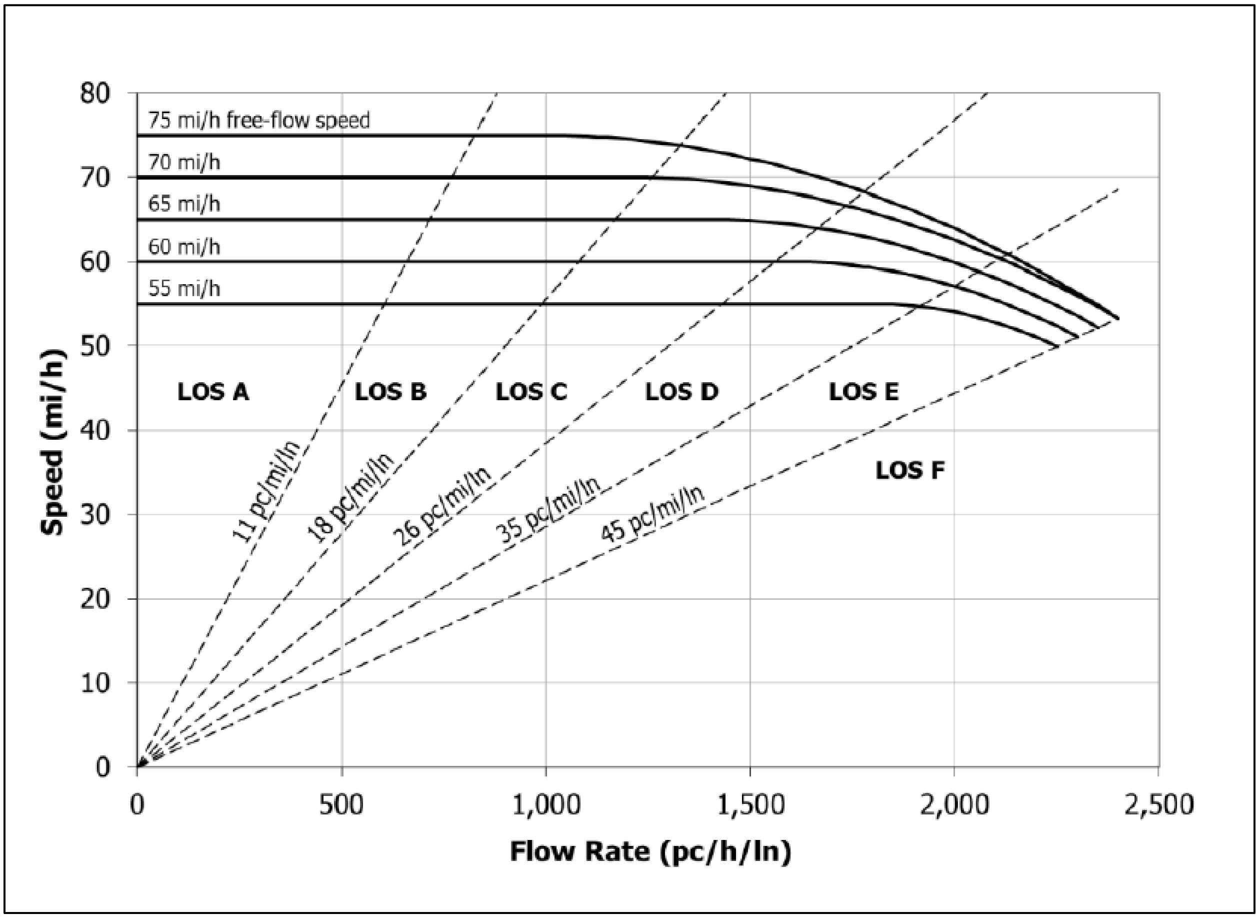
Note: Queue override logic and its effects are not shown in this flow chart.

Topic 3 Level of Service

The level of service (LOS) on freeway segments is defined in the 2016 *Highway Capacity Manual* (*HCM*) by density. Density describes a motorist's proximity to other vehicles and is related to a motorist's freedom to maneuver within the traffic stream. LOS is categorized into six levels from A through F.

The densities (passenger cars per mile per lane) and related speed and flow rates (passenger cars per hour per lane) for each LOS are shown in Figure 215-6.

Figure 215-6 Speed vs. Flow Rate (HCM 2016 Exhibit 12-16)



Source: Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine, 2016.

Even though ramp metering data is expressed in VPH per lane (see Section 5, "Data Collection"), speed vs. flow rates using either unit have similar shapes.

The flow rate limits for LOS F are any volumes that exceed LOS E. LOS F is an unstable (breakdown) flow. It occurs when a freeway is experiencing a greater demand than its capacity.

Topic 4 Level of Service Required to Start Active Ramp Metering

For recurring congestion, it is recommended that ramp metering begin when the traffic volume reaches LOS C.

For non-recurring congestion, it is recommended that ramp metering begin when the traffic volume reaches LOS D.

The flow rate required to start active ramp metering may need to be adjusted to incorporate the following unique freeway features:

- Blockages or queuing.
- Construction on or near the freeway.

Section 5 Data Collection

Topic 1 General

All flow rates and metering release rates shall be expressed in vehicles (or passenger cars) per hour per lane (or VPH per lane).

All speeds shall be expressed in miles per hour (mph).

All occupancies shall be expressed in percentage increments of 0.1%.

Topic 2 Mainline

Traffic volume and occupancy shall be available for each mainline lane.

Each mainline lane that uses inductive loop detectors shall have an upstream loop and downstream loop (dual loops).

Each mainline lane that has dual inductive loop detectors shall collect speed data.

Accuracy, as stated in the *Caltrans TMS Standardization Plan* (Final Draft 2003, Tables 4.3-1, 4.3-2, and 4.3-3), shall meet the following Caltrans Data Collection Accuracy standards:

- Mainline speeds shall be within ±5 mph.
- Mainline occupancy shall be within ±2%.
- Number of mainline vehicles passing over an inductive loop detector shall have an accuracy of ±2.5% (at 500 VPH).

Topic 3 Opposite Mainline

Traffic volume and occupancy shall be available for each opposite mainline lane. Dual inductive loop detectors in opposite mainline lanes shall make vehicle speed data available.

Accuracy, as stated in the *Caltrans TMS Standardization Plan* (Final Draft 2003, Tables 4.3-1, 4.3-2, and 4.3-3), shall meet the following Caltrans Data Collection Accuracy standards:

- Opposite mainline speeds shall be within ±5 mph.
- Opposite mainline lanes shall have an occupancy within ±2%.

The number of opposite mainline vehicles passing over an inductive loop detector shall have an accuracy of ±2.5% (at 500 VPH)

Topic 4 Metered Lanes

Volume and occupancy data shall be available from each queue, demand, and passage-detection location.

Accuracy, as stated in the *Caltrans TMS Standardization Plan* (Final Draft 2003, Tables 4.3-1, 4.3-2, and 4.3-3), shall meet the following Caltrans Data Collection Accuracy standards:

- **Demand Loop**: There shall be no missed vehicles in vehicle counts and a vehicle shall be detected within 100 milliseconds of its presence over the inductive loop detector.
- **Passage Loop**: There shall be no missed vehicles in vehicle counts and a vehicle shall be detected within 100 milliseconds of its presence over the inductive loop detector.

Topic 5 Other Data Collection Locations

Special detectors and inductive loop detectors at other data collection locations, such as off-ramps and C–D roads, shall make volume and occupancy data available for each detection location. On loops shall collect volume data. Accuracy of these devices shall conform to the *Caltrans TMS Standardization Plan* (Final Draft 2003, Tables 4.3-1, 4.3-2, and 4.3-3).

Topic 6 Poll Data

The ramp meter controller should calculate and transmit traffic data to the operating district's central system every 30 seconds.

Section 6 Communications

Topic 1 General

Transmission Control Protocol/Internet Protocol (TCP/IP) is the recommended method of communications from the operating district's central system to ramp metering field controllers.

Polling from the central traffic management system and a response from ramp metering field controllers shall be the recommended method of communications.

When ramp metering field controllers have an operating system that allows remote access, secure shell (SSH) shall be the recommended method of remotely accessing the ramp metering controllers.

When ramp metering field controllers have an operating system that allows file transfers, secure file transfer protocol (SFTP) shall be the recommended method of remotely accessing the ramp metering controllers.

Topic 2 Polling Protocols

The following polling protocols are currently used by ramp metering programs in California:

- San Diego Ramp Metering System (SDRMS) (used by Districts 3, 5, 6, 10, 11).
- Semi-Autonomous Ramp Metering System (SATMS) (used by Districts 7, 12).
- Orange Country Ramp Metering System (OCRMS) (used by District 12).
- Rev8 (used by Districts 6, 8), on Linux Operating System for Model 2070 LX controllers.
- Traffic Operating System (TOS) (used by District 4).
- Universal Ramp Metering Software (URMS) (used by Districts 3, 4, 7, 10).

Topic 3 Remote Configuration Protocols

The following remote configuration protocols are currently used by ramp metering programs in California:

- SDRMS (used by Districts 3, 5, 6, 10, 11).
- SATMS (used by Districts 7, 12).
- TOS (used by District 4).
- Rev8 (used by Districts 6, 8).

Section 7 Freeway-to-Freeway Connector Metering

Topic 1 General

Connector metering is used to ensure more efficient merging, such as breaking up vehicle platoons and managing traffic demand from one freeway to another. Their operation and purpose are similar to an ordinary ramp meter. However, there are additional issues that may raise concerns.

Topic 2 Discharge Rate

Freeway-to-freeway connectors usually have a very high traffic demand. It is recommended that to prevent vehicles from queueing to the upstream connector, the discharge rate be the highest rate allowable for the specified number of vehicles per green (VPG) (see Section 12, "Cycle Length and Discharge Rates").

Metering with three VPG is not recommended.

Topic 3 Freeway-to-Freeway Connector Queue Usage

Queue detectors shall be used to detect queue extensions caused by the connector meter. If the queue is likely to extend onto the upstream freeway, the connector meter should be set to suspend metering operations by advancing to the pre-metering green interval. If this happens on a recurring basis, the freeway-to-freeway connector should not be metered.

Topic 4 Advance Warning Signs

On freeway-to-freeway connectors, it is recommended that activated blank-out signs be used for advance warning of active ramp metering operations.

On freeway-to-freeway connectors, it is recommended that each activated blank-out sign be equipped with a normally open or normally closed contact, which shall be connected to the controller so that the controller will suspend ramp metering operations by advancing to the pre-metering green interval if the advance warning sign is no longer illuminated.

Section 8 Special Functionality

Topic 1 Priority Vehicle (Bus) Bypass

When on-ramps are actively metered and priority vehicle bypass is offered, the following logistical sequence shall be used once the request for priority vehicle bypass is received by the ramp metering system:

- Signal indications on all lanes other than the priority lane shall be advanced to and held in the metering red interval.
- Signal indications on the priority lane shall be advanced to and held in the metering green interval.
- Priority vehicle bypass shall terminate when the priority vehicle is detected by the passage detector or when priority vehicle bypass is no longer requested, whichever occurs first.
- At the termination of priority vehicle bypass, the signal indications on the priority lane shall be advanced to the metering yellow interval. Once the metering yellow interval has expired, the signal indications on the priority lane shall be advanced to the metering red interval and the ramp meter shall resume normal metering operations.

It is recommended that no more than one metered lane on an on-ramp be selected as a priority lane.

There shall be a user-settable timeout to prevent priority vehicles from inadvertently activating the priority bypass and prolonging it indefinitely. The timeout shall have a range of 0 to 255 seconds. A value of 0 shall disable the timeout functionality.

Topic 2 Emergency Vehicle Preemption

When on-ramps are actively metered and emergency vehicle preemption is needed, the following logic sequence shall be applied:

- If the meter is in the initialization or pre-metering non-green interval (dark), then the ramp meter shall be held in the pre-metering non-green interval until the preemption request is terminated.
- If the meter is in the pre-metering green interval, then the ramp meter shall be held in this interval until the preemption request is terminated.
- If the metering is in any other interval, then the ramp meter shall advance until the ramp is in the pre-metering green interval. Once in the pre-metering green interval, the meter shall be held in this interval until the preemption request is terminated.

Topic 3 Reversible Lanes

It is recommended that ramp meters be able to detect mainline traffic flow direction in cases where reversible mainline lanes are used.

Section 9 Developing a Local Traffic-Responsive Ramp Metering Plan Using Performance Measurement System Data

Topic 1 General

The following section describes how to use the data stored in the Caltrans Performance Measurement System (PeMS) to calculate local traffic-responsive plans. PeMS data is available on the PeMS website. There are many methods and formulas that can be used to develop locally traffic-responsive ramp metering plans. Various strategies can also be used. A primary strategy is to meter ramps to manage demand upstream of a freeway's bottleneck. In urban areas with long peak periods, it might be preferred to meter at demand to prevent queues from extending beyond the upstream end of the ramp. Local agencies might request lengthy metering cycles to discourage cut-through traffic. During shorter peak periods, or when the demand-to-capacity ratio is relatively small, it is easier to meter faster than demand to minimize delay on the ramp. This example reflects such a strategy.

Topic 2 Steps to Find Critical Values Used to Create a Local Traffic-Responsive Ramp Metering Plan

The following is a list of steps that can be used to find the critical values used in the creation of a local traffic-responsive ramp metering plan. This list of steps uses LOS as the controlling criterion of ramp metering. Other criteria, including mainline occupancy and mainline speed, could also be used. A sample calculation is shown in Section 9, Topic 3 "Example of Creating a Traffic-Responsive Plan Using PeMS Data." Each step uses data available in PeMS:

1. Find the PeMS controller identification (ID) for the ramp metering location.
2. Find the PeMS ID (the vehicle detector station [VDS] number) for the metered lane data.
3. Find the PeMS ID (the VDS number) for the mainline lane data.
4. Determine the number of lanes to be metered.
5. Determine the number of mainline lanes.
6. Determine the mainline design speed limit.
7. Determine the maximum number of vehicles entering the freeway from the on-ramp (peak-hour volume).
8. Determine the maximum VPH per lane the section of freeway can support.

9. Determine the LOS C volume for the design speed limit.
10. Determine the occupancies on the mainline adjacent to the on-ramp merge point when LOS C is reached.
11. Determine the time of day the section of freeway deteriorates to LOS C from LOS B.
12. Determine the time of day the section of freeway leaves LOS C to LOS B.
13. Determine the metering rate for when the freeway enters LOS C.
14. Determine the LOS D volume for the design speed limit.
15. Determine the occupancy on the mainline adjacent to the on-ramp merge point when LOS D is reached.
16. Determine the occupancy when the occupancy-to-volume ratio is no longer linear.
17. Determine the critical mainline volume.

Topic 3 Example of Creating a Local Traffic-Responsive Plan Using Performance Measurement System Data

The following is an example of how to use each step shown in Section 9, Topic 2 "Steps to Find Critical Values Used to Create a Local Traffic-Responsive Ramp Metering Plan," to determine the critical values of a local traffic-responsive ramp metering plan. State Route 51 (SR-51/Interstate 80 Business/Capital City Freeway) northbound at 30th and E Streets in Sacramento during the weekdays of November 5, 2018, through November 9, 2018, is used in this example. For reference, the GPS coordinates for the location used in this example are: 38.579513, -121.464424.

Step 1 Example

Find the PeMS controller ID for the ramp metering location.

After logging into PeMS and being directed to the home page, click on "Facilities & Devices" > "Freeways" > "SR51-N." The controller ID is 312731 for the ramp metering location.

Table 215-3 Controller ID From PeMS

Freeway	District	County	City	CA PM	Abs PM	Length	ID	Name	Lanes	Stn Type	Sensor Type	HOV	Controller ID
SR51-N	3	Sacramento	Sacramento	.079	0.08	0.000	314195	T St.	1	Off Ramp	Loops	No	312809
-	-	-	-	1.50	1.50	0.420	312745	30 & E St.	3	Mainline	Loop	No	312731
-	-	-	-	1.50	1.50	0.000	312746	30 & E St.	2	On-Ramp	Other	No	312731

Step 2 Example

Find the PeMS ID (the VDS number) for the metered lane data.

The ID is 312746 for the on-ramp.

Step 3 Example

Find the PeMS ID (the VDS number) for the mainline lane data.

The ID is 312745 for the mainline.

Step 4 Example

Determine the number of lanes to be metered.

There are two metered lanes at this location.

Step 5 Example

Determine the number of mainline lanes.

There are three mainline lanes at this location.

Step 6 Example

Determine the mainline design speed limit.

Click on the station's "ID" (in this example, it is 312745) for the mainline. Shown in PeMS, the "Roadway Information (from TSN)" box, the design speed limit is 70 mph (as depicted from PeMS, in Table 215-4).

Table 215-4 Design Speed Limit from PeMS

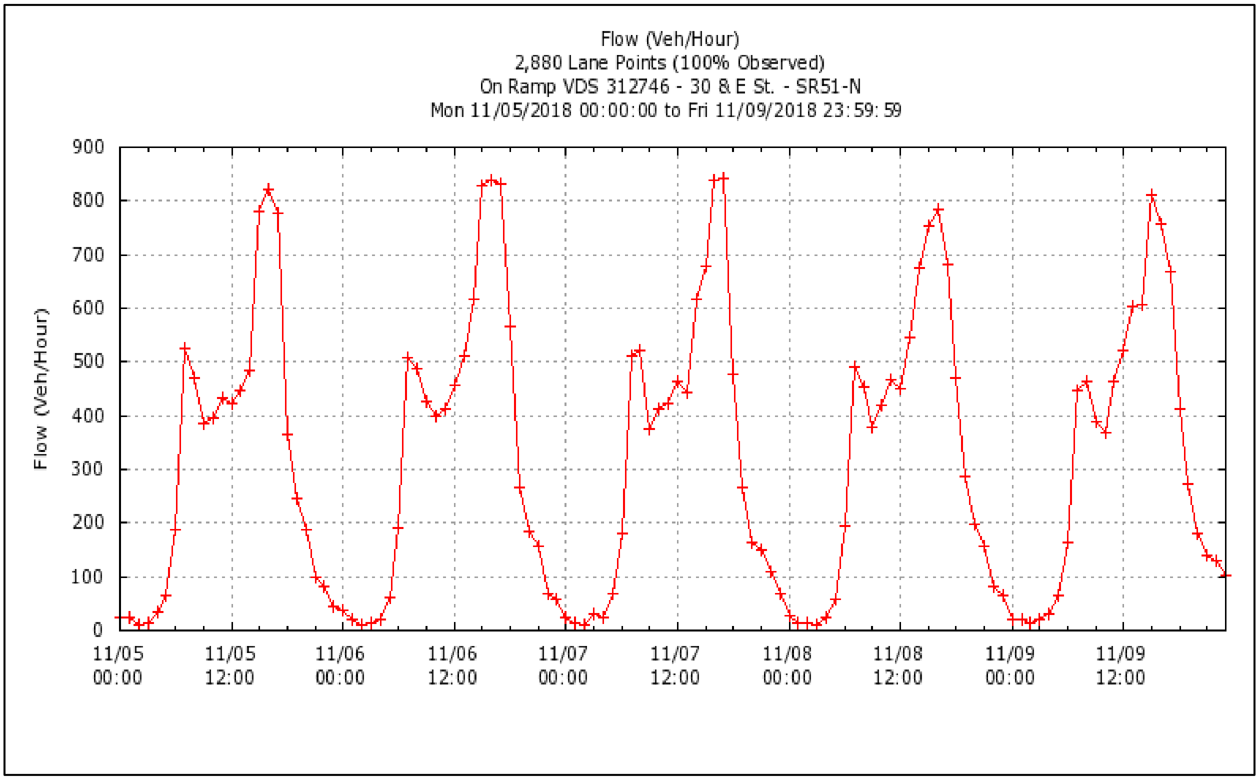
Roadway Information Categories (From TSN)	**Roadway Information (From TSN)**
Road Width	48 ft.
Lane Width	16.0 ft.
Inner Shoulder Width	8 ft.
Inner Shoulder Treated Width	8 ft.
Outer Shoulder Width	8 ft.
Outer Shoulder Treated Width	8 ft.
Design Speed Limit	70 mph
Functional Class	Principal Arterial w/ C/L Prin. Arterial
Inner Median Type	Unpaved
Inner Median Width	36 ft.
Terrain	Flat

Step 7 Example

Determine the maximum number of vehicles entering the freeway from the on-ramp.

Go back to the “Facilities & Devices page and click on the station’s ID (in this example, it is 312746). Go to “Performance” > “Aggregates” > “Time Series.” The Monday, Tuesday, Wednesday, Thursday, and Fridays should be checked. Click the “Draw Plot” button. The graph in Figure 215-7 shows the hourly number of vehicles entering the freeway at the on-ramp location. Be aware that since ramp metering operations are already in place, the discharge rate volume is limited by the current metering rates used at that location. Queues during metering hours would indicate a greater demand than shown in PeMS.

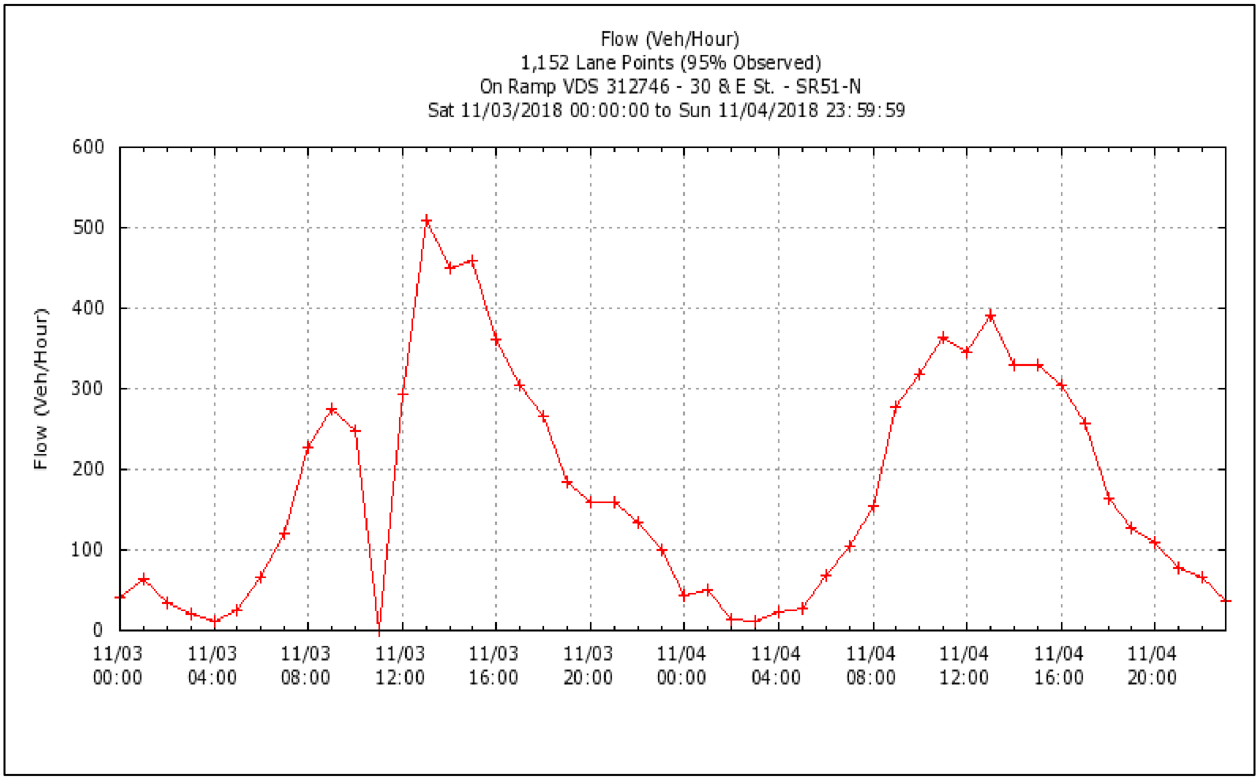
Figure 215-7 Hourly Weekday Meter Lane Volume Data for November 5-9, 2018, from PeMS



The PeMS vehicle flow graph shown in Figure 215-7 generally shows that during the week, the maximum on-ramp flow rate is 850 VPH. This equates to approximately 425 VPH for each of the two metered lanes.

Check weekends to determine if there are any periods that exceed weekday volumes. The graph shown in Figure 215-8 for November 3 and November 4 shows the highest on-ramp volume was just over 500 VPH, well below the 850 VPH recorded during the following weekdays.

Figure 215-8 Weekend On-Ramp Traffic for November 3-4, 2018, from PeMS



Step 8 Example

Determine the maximum VPH per lane that the section of freeway can support.

Use “PeMS Performance” > “Aggregates” > “Time Series” function for the mainline (ID 312745) to determine capacity for the three mainline lanes. Figure 215-9 shows the capacity is approximately 5,400 VPH. The graph also shows there appears to be no major deviations between each weekday. Since there are three lanes, each lane’s capacity is approximately 1,800 VPH. If the demand exceeds this number, throughput on the freeway reduces.

Figure 215-9 Hourly Mainline Volume and Occupancy November 5-9, 2018, from PeMS

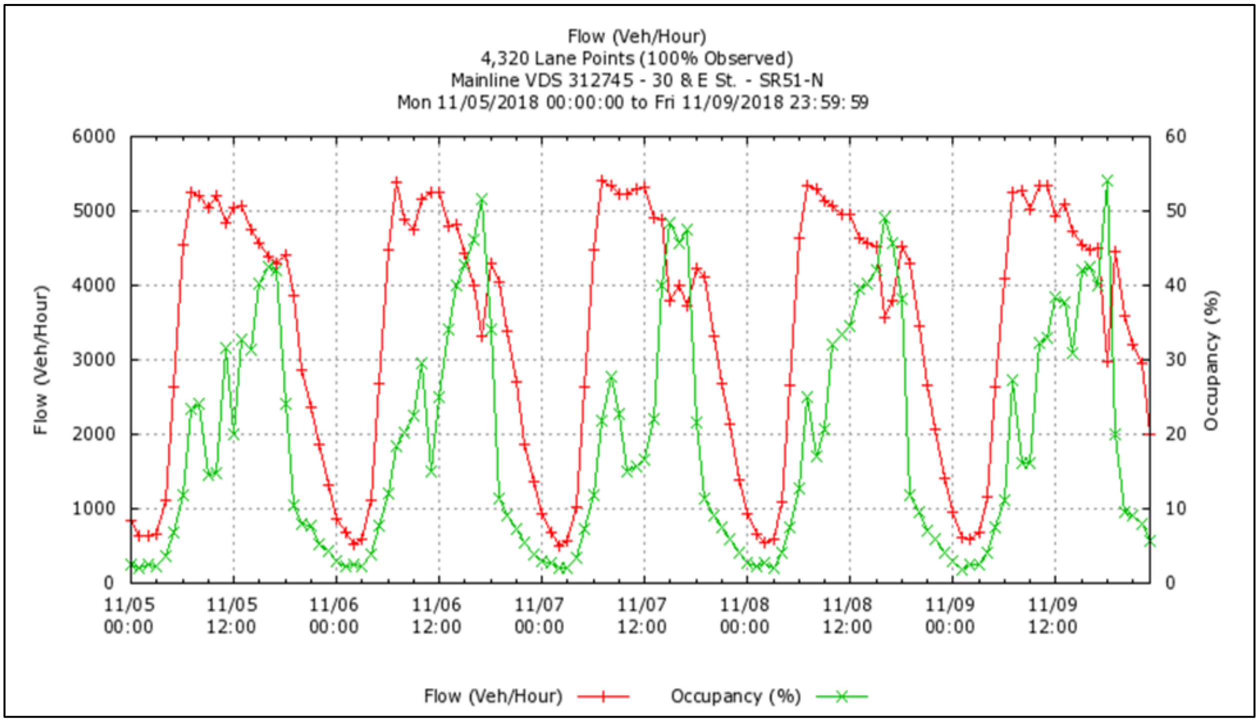
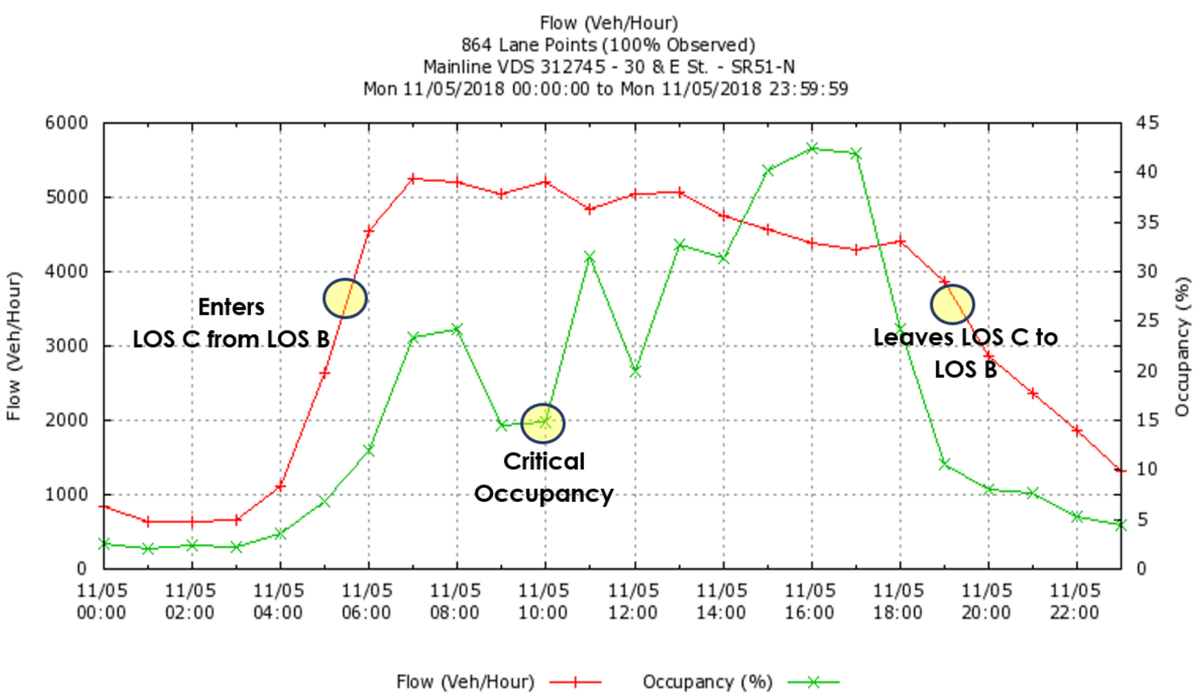


Figure 215-10 Hourly Mainline Volume and Occupancy Data for Monday, November 5, 2018, from PeMS



Step 9 Example

Determine the LOS C volume for the design speed limit.

From the *HCM* 2016 Exhibit 12-16 shown in Section 4, Topic 3 "Level of Service," the lower flow rate for LOS C at a design speed of 70 mph is 1,260 VPH per lane, or 3,780 VPH. Ramp meters should activate before demand exceeds this number and deactivate after demand reduces below this number (determined in 11 and 12 below). Check to ensure this volume does not exceed the maximum VPH per lane calculated in Step 8 (in this case, 1,800 VPH per lane).

Step 10 Example

Determine the occupancy on the mainline adjacent to the on-ramp merge point when LOS C is reached.

From PeMS 5-minute data, the flows are no longer in VPH per lane, but rather in vehicles per 5-minute time increments per lane. Therefore, a LOS C VPH of 3,780 equates to 315 vehicles every 5 minutes (3,780 ÷ 12).

To find the occupancy at 315 vehicles every five minutes, from the "Mainline VPS 312745 – 30 & E St" PeMS page, go to "Performance > Aggregates > Time Series". Input the appropriate dates and times. For Quantity select "Flow," for Granularity select "5 Minutes", for Lanes select "Agg", and for second quantity select "Occupancy". Select "Draw Plot" or "View Table." The occupancy at 315 vehicles is 10.0% (see Figure 215-11).

Step 11 Example

Determine the time of day the section of freeway deteriorates to LOS C from LOS B.

As per Section 4, Topic 4 "Level of Service Required to Start Active Ramp Metering," it is recommended that ramp metering for recurrent congestion begin when the traffic volume reaches LOS C. The November 5 data shows this section of freeway deteriorated to LOS C at approximately 5:30 a.m. Analysis of additional data from other peak periods will yield more reliable estimates of when the section of freeway deteriorates to LOS C. For brevity, 5:30 a.m. will be used as the time of day when the section of freeway deteriorates to LOS C from LOS B.

This is also the time when off-peak metering ends during non-recurrent congestion, and peak-period metering begins during recurrent congestion.

Step 12 Example

Determine the time of day the section of freeway improves from LOS C to LOS B.

The November 5 data show volumes exceeded 1,260 VPH per lane, or 3,780 VPH, until 7:30 p.m. Analysis of additional data from other peak periods will yield more reliable estimates of when the section of freeway improves from LOS C.

This is also the time when off-peak metering begins during non-recurrent congestion, and peak-period metering ends during recurrent congestion.

Step 13 Example

Determine the metering rate for when the freeway deteriorates to LOS C.

The available capacity when LOS C begins is 5,400 – 3780 = 1,620 VPH. For two metered lanes, each lane could be metered at 1,620 ÷ 2 or 810 VPH per lane. Even though the PeMS data show the typical demand from this on-ramp never gets this high, this is the maximum possible release rate per lane in case of an unexpected high demand after ramp metering begins. This releases queueing vehicles as quickly as possible and reduces the possibility of the queue extending beyond the upstream end of the ramp.

Step 14 Example

Determine the LOS D volume for the design speed limit.

As per Section 4, Topic 4 "Level of Service Required to Start Active Ramp Metering," it is recommended that ramp metering for non-recurrent congestion begin when the traffic volume reaches LOS D. From the *HCM* 2016 Exhibit 12-16 shown in Section 4, Topic 3 "Level of Service," the lower flow rate for LOS D at a design speed of 70 mph is 1,770 VPH per lane. Check to ensure this volume does not exceed the maximum VPH per lane calculated in Step 8 (in this case, 1,800 VPH per lane). If the calculated LOS D volume exceeds the maximum volume that this section of freeway can support, use the lesser of the two numbers.

Step 15 Example

Determine the occupancy on the mainline adjacent to the on-ramp merge point when LOS D is reached.

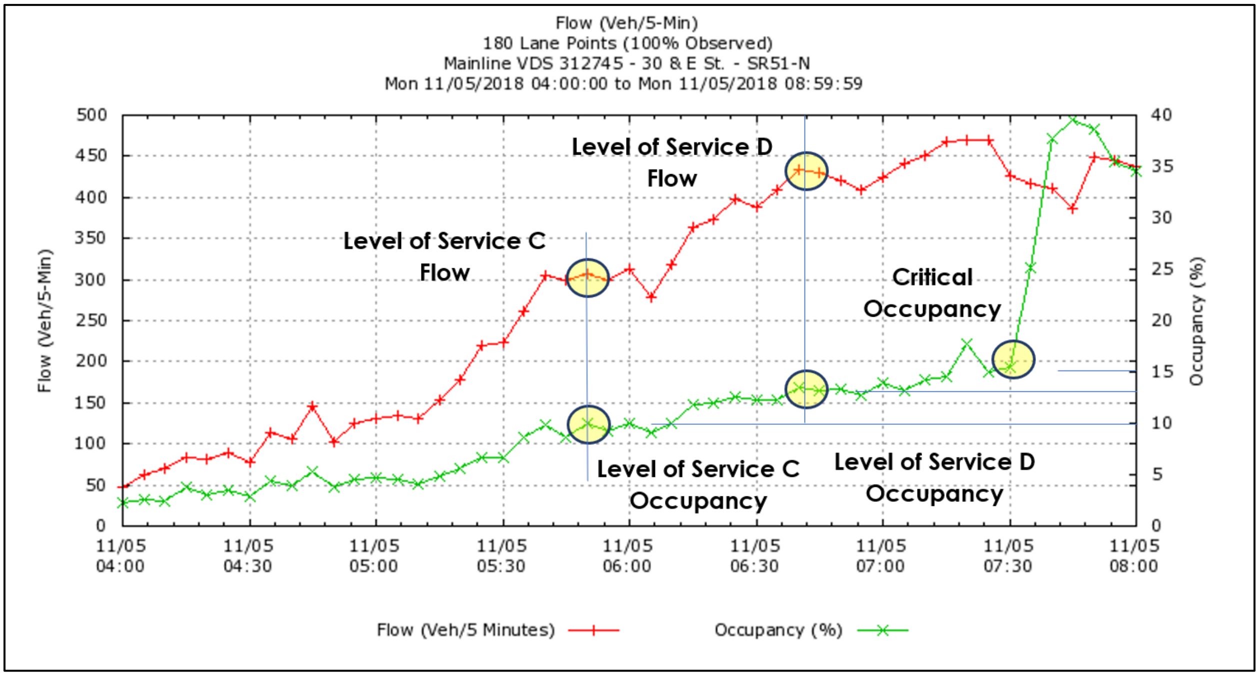
LOS D of 5,310 VPH equals 442 vehicles every five minutes (5,310 ÷ 12). To find the occupancy at 442 vehicles every five minutes, from the "Mainline VPS 312745 – 30 & E St" PeMS page, go to "Performance > Aggregates > Time Series". Input the appropriate dates and times. For Quantity select "Flow," for Granularity select "5 Minutes", for Lanes select "Agg", and for second quantity select "Occupancy". Select "Draw Plot" or "View Table." The occupancy at 442 vehicles is 13.2%. See Figure 215-11.

Step 16 Example

Determine the occupancy when the occupancy-to-volume ratio is no longer linearly proportional.

From PeMS 5-minute data (see Figure 215-11), the fitted occupancy and flow graphs are proportional until occupancy increases significantly. This occurs after the occupancy reaches 15.0% and is when traffic flow breaks down (LOS F).

Figure 215-11 Five-Minute Mainline Volume and Occupancy for Monday, November 5, 2018, from PeMS



Step 17 Example

Determine the critical mainline volume.

For recurring congestion (LOS C limit):

$$Critical\ Mainline\ Volume = Downstream\ Capacity - On\text{-}ramp\ Volume$$

Thus, the *Critical Mainline Volume* is equal to:

Downstream Capacity = 5,400 (1,800 VPH per lane) minus the maximum allowable *On-ramp Volume* of 810 VPH per lane, or 5,400 – 1,620 = 3,780 VPH for the section of the freeway, or 1,260 VPH per lane for each of the three mainline lanes. Thus, ramp metering will begin when the freeway enters LOS C. The metering may allow as many as 810 VPH per lane before the downstream section will become congested. Special consideration should be given to other operational factors, such as on-ramp volume from downstream on-ramps.

And for the slowest discharge rate, the freeway has capacity that could allow metering at demand. Metering at demand allows for minimal queues on the ramp.

Note that during off-peak periods, vehicles may be discharged at a rate as high as 900 VPH per lane to break up platoons entering the freeway.

The results from the above example are shown in Figure 215-12 (see Appendix 215 A, "Useful Forms," for a blank Traffic Responsive Worksheet).

Figure 215-12 Example Traffic Responsive Worksheet

Traffic Responsive Worksheet					
Rte/Dir		Post Mile		Engineer	EXAMPLE
Ramp Meter Name		EXAMPLE	Date(s)		

1	LDS number	321731
2	VDS number for the metered lane(s)	312746
3	VDS number for the mainline lanes	312745
4	Number of metered lanes	2
5	Number of mainline lanes	3
6	Mainline design speed limit, in mph	70
7	Maximum number of vehicles entering the freeway from the onramp, in VPH per lane	425
8	Maximum VPH per lane that the section of freeway can support	1,800
9	LOS C volume for design speed limit, in VPH per lane	1,260
10	Occupancy on mainline when LOS C is reached	10.0%
11	Time of day that the section of freeway enters LOS C from LOS B	05:30
12	Time of day that the section of freeway leaves LOS C to LOS B	19:30
13	Determine the metering rate for when the freeway enters LOS C, in VPH per lane	810
14	LOS D volume for design speed limit, in VPH per lane	1,770
15	Occupancy on mainline adjacent to merge point when LOS D is reached	13.2%
16	Occupancy, when the occupancy-to-volume ratio is no longer linearly proportional (break down occupancy)	15.0%
17	Calculate Critical Mainline Volume = (mainline volume * number of mainline lanes) – (metered lane volume * number of metered lanes) ÷ number of mainline lanes	([1,800 * 3] – [810 * 2]) ÷ 3 = 1,260

Metering Rates During Peak Hours based on LOS C			
	Discharge Rate (VPH per lane)		**Occupancy (%)**
Highest Discharge Rate	810 (step 13)		10.0 (step 10)
Slowest Discharge Rate	425 (step 7)		13.2 (step 15)
Start Time	05:30 (step 11)	**Stop Time**	19:30 (step 12)

Metering Rates During Off-Peak Hours based on LOS D			
	Discharge Rate (VPH per lane)		**Occupancy %**
Highest Discharge Rate	900 (max rate 1 VPG)		15.0 (step 16)
Slowest Discharge Rate	900 (max rate 1 VPG)		15.0 (step 16)
Start Time	19:30 (step 12)	**Stop time**	05:30 (step 11)

Section 10 Turn-On Procedures for New Ramp Metering Locations

Topic 1 General

Each ramp metering location should be set to pre-metering green during typical metering hours for at least one week prior to when the ramp meter will initially advance to non-green startup warning or green startup warning. The district should consider placing signage at the ramp meter location to inform motorists that the ramp meter will cycle. The signage should have the date of the ramp meter's cycling implementation. In addition, the district should consider conducting a public awareness campaign prior to the posted date.

The district should send notifications to the California Highway Patrol and to affected local agencies on implementing the ramp meter's cycling.

Topic 2 Reactivated Ramp Meter

When reactivating a ramp meter that has been deactivated for more than six months, the district should leave the ramp meter on pre-metering green during typical metering hours for at least one week prior to actual meter startup.

Section 11 Settable Parameters

Topic 1 General

The following are common user-settable parameters for ramp metering operations. View the *Universal Ramp Metering Software User Manual* on Caltrans Onramp for a detailed explanation of the items.

Table 215-5 Common User-Settable Parameters for Ramp Metering Operations

Item	Min	Max	Special Value	Units
Global				
Number of Metered Lanes	1	4	0	Lanes
Number of Mainline Lanes	1	8	0	Lanes
Number of Opposite Lanes	1	8	0	Lanes
Number of Additional Detector Locations	1	16	0	Lanes
Daylight Savings	Yes, No			
HOV Active	Yes, No			
Failsafe Feedback Enabled	Yes, No			
Reboot on Loss of Communications	Yes, No			
Serial Communications Port				
Baud Rate	1,200, 2,400, 4,800, 9,600, 19,200, 38,400			
Data Bits	5, 6, 7, 8			
Parity	Odd, Even, None			
Stop Bit	1, 2			
Handshaking	None, Normal, Auto, Auto CTS, Auto RTS			
RTS On Time	1	255	0	Milliseconds
Address (Drop Number)	1	255		
Ethernet Communications Port				
Address (Drop Number)	1	255	0	
Port Number	1	65535	0	
IP Mode	Static, DHCP			
Address	1	255	0	IP Address Format
Network Mask	1	255	0	IP Address Format
Broadcast	1	255	0	IP Address Format
Gateway	1	255	0	IP Address Format
Additional Detectors				
Detector Mode	Enabled, Disabled			
Max Presence Threshold	1	1,500	0	Minutes

Item	Min	Max	Special Value	Units
No Activity Threshold	1	1,500	0	Minutes
Mainline Lane				
Lane Mode	Disabled, Lead, Trail, Dual, Pre-Processed			
Lead Zone Length	0.1	15.0	0.0	0.1-Feet
Trail Zone Length	0.1	15.0	0.0	0.1-Feet
Speed Trap Spacing	0.1	60.0	0.0	0.1-Feet
Maximum Presence Threshold	1	720	0	Minutes
Typical Vehicle Length	0.1	45.0	0.0	0.1-Feet
HOV Lane	Yes, No			
REV Lane	Yes, No			
Metered Lane				
Lane Enabled	Yes, No			
Queue Detection Mode	Disabled, Occupancy			
Queue Adjustment Mode	Rate, Fixed, Shutdown Meter			
Queue Maximum Presence Threshold	1	720	0	Minutes
Queue No Activity Threshold	1	720	0	Minutes
Queue Dependent Max Presence Threshold	1	600	0	Seconds
Queue Occupancy Lower Limit	0.0	99.9	None	0.1%
Queue Occupancy Lower Limit	0.0	99.9	None	0.1%
Queue Adjustment Rate	5	1,800	0	Vehicles per Hour
Queue Adjustment Rate Iterations	1	20	0	Iterations
Queue Replacement Rate	600	1,800	None	Vehicles per Hour
Demand Detector Mode	Enabled, Recall, Red Lock			
Demand Max Presence Threshold	1	720	0	Minutes
Demand No Activity Threshold	1	720	0	Minutes
Demand Dependent Maximum Presence Threshold	1	600	0	Seconds
Demand Dependent No Activity Threshold	1	30	0	Vehicles per 30 Seconds
Passage Detector Mode	Enabled, Disabled			
Passage Erratic Count Threshold	1	255	0	Minutes
Passage Maximum Presence Threshold	1	720	0	Minutes
Passage No Activity Threshold	1	720	0	Minutes
Dependency Group	A, B, C			
Minimum Metering Time	1	60	0	Minutes
Minimum Non-Metering Time	1	60	0	Minutes
Maximum Pre-Green	0	255	0	Minutes
Startup Alert Time	0.1	60.0	0.0	0.1-Seconds
Startup Warning Time	0.1	60.0	0.0	0.1-Seconds

Item	Min	Max	Special Value	Units
Startup Green Time	0.1	60.0	0.0	0.1-Seconds
Startup Yellow Time	0.1	10.0	0.0	0.1-Seconds
Startup Red Time	0.1	10.0	0.0	0.1-Seconds
Minimum Red Time	1.0	15.0	None	0.1-Seconds
Demand Gap Time	1.0	15.0	0.0	0.1-Seconds
Demand Red Time	1.0	15.0	0.0	0.1-Seconds
Minimum Green Time	1.0	5.0	None	0.1-Seconds
Maximum Green Time	1.0	15.0	None	0.1-Seconds
Yellow Time	0.5	5.0	0.0	0.1-Seconds
Shutdown Warning Time	1	600	0	Seconds
Post-Metering Green Time	0.1	60.0	0.0	0.1-Seconds
Vehicles per Green	1	3	None	Vehicles
Platoon Metering	Yes, No			
HOV Lane	Yes, No			
Bus Lane	Yes, No			
Plan Entry				
Metering Discharge Rate	150	1,800	0	Vehicles per Hour
Occupancy Threshold	0.1	99.9	0.0	0.1%
Flow Rate Threshold	500	3,600	0	Vehicles per Hour
Speed Threshold	10	99	0	Miles per Hour
Month	NC, Jan., Feb., Mar., Apr., May, Jun., Jul., Aug., Sep., Oct., Nov., Dec.			
Week	1	5	None	Week Number
Day	Sun, Mon, Tue, Wed, Thu, Fri, Sat, Holiday			
Dependency Group				
Signal Service Mode	MUTEX, Fractional Offset			

Section 12 Cycle Length and Discharge Rates

Topic 1 General

A cycle length longer than 15.0 seconds is not recommended due to the probability that it will increase the likelihood of violations. A cycle length shorter than 4.0 seconds for one car per green, 6.0 seconds for two cars per green, and 8.0 seconds for three cars per green is not recommended due to the increased probability of driver confusion.

Formulas for discharge rates and cycle lengths, as well as calculated discharge rate and cycle lengths, are shown below:

$$Cycle\ Length(seconds/cycle) = \frac{3{,}600(seconds/hour)\ \times (Number\ of\ vehicles\ per\ green\ per\ lane)}{Discharge\ Rate(vehicles/hour)}$$

Table 215-6 Cycle Time vs. Discharge Rate

Cycle Length Seconds	Discharge Rate, Vehicles Per Hour Per Lane - One VPG	Discharge Rate, Vehicles Per Hour Per Lane - Two VPG	Discharge Rate, Vehicles Per Hour Per Lane - Three VPG
Less than 4.0	N/A	N/A	N/A
4.0	900	N/A	N/A
4.5	800	N/A	N/A
5.0	720	N/A	N/A
5.5	654	N/A	N/A
6.0	600	1,200	N/A
6.5	554	1,108	N/A
7.0	514	1,029	N/A
7.5	480	960	N/A
8.0	450	900	1,350
8.5	423	847	1,271
9.0	400	800	1,200
9.5	379	758	1,137
10.0	360	720	1,080
10.5	343	686	1,029
11.0	327	654	982
11.5	313	626	939
12.0	300	600	900
12.5	288	576	864
13.0	277	554	831
13.5	267	533	800
14.0	257	514	771

Cycle Length Seconds	Discharge Rate, Vehicles Per Hour Per Lane - One VPG	Discharge Rate, Vehicles Per Hour Per Lane - Two VPG	Discharge Rate, Vehicles Per Hour Per Lane - Three VPG
14.5	248	497	745
15.0	240	480	720
Greater than 15.0	N/A	N/A	N/A

To find the discharge rate, use the following formula:

$$Vehicles\ per\ hour\ per\ lane = \frac{3{,}600(seconds/hour) \times (Number\ of\ vehicles\ per\ green\ per\ lane)}{Ramp\ Meter\ Cycle\ Length(seconds/cycle)}$$

Table 215-7 Discharge Rate vs. Cycle Time

Discharge Rate in Vehicles Per Hour/Lane	Cycle Length in Seconds Start of Metering Green Interval to Start of Metering Green Interval -One Vehicle Per Green	Cycle Length in Seconds Start of Metering Green Interval to Start of Metering Green Interval - Two Vehicles Per Green	Cycle Length in Seconds Start of Metering Green Interval to Start of Metering Green Interval - Three Vehicles per Green
1,350	N/A	N/A	8.0
1,300	N/A	N/A	8.3
1,250	N/A	N/A	8.6
1,200	N/A	6.0	9.0
1,150	N/A	6.3	9.4
1,100	N/A	6.5	9.8
1,050	N/A	6.9	10.3
1,000	N/A	7.2	10.8
950	N/A	7.6	11.4
900	4.0	8.0	12.0
850	4.2	8.5	12.7
800	4.5	9.0	13.5
750	4.8	9.6	14.4
720	5.0	10.0	15.0
700	5.1	10.3	N/A
650	5.5	11.1	N/A
600	6.0	12.0	N/A
550	6.5	13.1	N/A
500	7.2	14.4	N/A
480	7.5	15.0	N/A
450	8.0	N/A	N/A
400	9.0	N/A	N/A

Discharge Rate in Vehicles Per Hour/Lane	Cycle Length in Seconds Start of Metering Green Interval to Start of Metering Green Interval -One Vehicle Per Green	Cycle Length in Seconds Start of Metering Green Interval to Start of Metering Green Interval - Two Vehicles Per Green	Cycle Length in Seconds Start of Metering Green Interval to Start of Metering Green Interval - Three Vehicles per Green
350	10.3	N/A	N/A
300	12.0	N/A	N/A
250	14.4	N/A	N/A
240	15.0	N/A	N/A
200	N/A	N/A	N/A

Section 13 Startup and Metering Yellow Time Calculation

The following tables show calculated yellow time in seconds based on the following formula, as stated in the Institute of Transportation Engineers *Traffic Engineering Handbook*.

$$Y = t + 1.467S \div (2a + 64.4g)$$

With the following values:

Table 215-8 Yellow Time Calculation Values

Value	Definition
Y	Yellow time in seconds
t = 1.0 seconds	Driver reaction time in seconds
*S	Speed in mph
a = 10.0	Deceleration rate in ft/sec^2
g	Slope of the ramp (a downward 2.5% slope = -0.025)

*A value of 10 mph may be used when queues are expected.

Table 215-9 Yellow Time Calculation for Downhill Slope (in Seconds)

Speed (mph)	Downhill Slope 0%	Downhill Slope -1%	Downhill Slope -2%	Downhill Slope -2.5%	Downhill Slope -3%	Downhill Slope -4%	Downhill Slope -5%
5	1.4	1.4	1.4	1.4	1.4	1.4	1.4
10	1.7	1.8	1.8	1.8	1.8	1.8	1.9
15	2.1	2.1	2.2	2.2	2.2	2.3	2.3
20	2.5	2.5	2.6	2.6	2.6	2.7	2.7
25	2.8	2.9	3.0	3.0	3.0	3.1	3.2
30	3.2	3.3	3.4	3.4	3.4	3.5	3.6
35	3.6	3.7	3.7	3.8	3.8	3.9	4.1
40	3.9	4.0	4.1	4.2	4.2	4.4	4.5
45	4.3	4.4	4.5	4.6	4.7	4.8	4.9
50	4.7	4.8	4.9	5.0	5.1	5.2	5.4
55	5.0	5.2	5.3	5.4	5.5	5.6	5.8

Speed (mph)	Downhill Slope 0%	Downhill Slope -1%	Downhill Slope -2%	Downhill Slope -2.5%	Downhill Slope -3%	Downhill Slope -4%	Downhill Slope -5%
60	5.4	5.5	5.7	5.8	5.9	6.1	6.2
65	5.8	5.9	6.1	6.2	6.3	6.5	6.7

Table 215-10 Yellow Time Calculation for Uphill Slope (in Seconds)

Speed (mph)	Uphill Slope 0%	Uphill Slope +1%	Uphill Slope +2%	Uphill Slope +2.5%	Uphill Slope +3%	Uphill Slope +4%	Uphill Slope +5%
5	1.4	1.4	1.3	1.3	1.3	1.3	1.3
10	1.7	1.7	1.7	1.7	1.7	1.6	1.6
15	2.1	2.1	2.0	2.0	2.0	2.0	1.9
20	2.5	2.4	2.4	2.4	2.3	2.3	2.3
25	2.8	2.8	2.7	2.7	2.7	2.6	2.6
30	3.2	3.1	3.1	3.0	3.0	2.9	2.9
35	3.6	3.5	3.4	3.4	3.3	3.3	3.2
40	3.9	3.8	3.8	3.7	3.7	3.6	3.5
45	4.3	4.2	4.1	4.1	4.0	3.9	3.8
50	4.7	4.6	4.4	4.4	4.3	4.2	4.2
55	5.0	4.9	4.8	4.7	4.7	4.6	4.5
60	5.4	5.3	5.1	5.1	5.0	4.9	4.8
65	5.8	5.6	5.5	5.4	5.3	5.2	5.1